Gamma-Ray Energies in the Decay of ^{38}Cl

K. S. Krane and M. L. Keck

Department of Physics, Oregon State University, Corvallis, OR 97331

E. B. Norman and A. P. Shivprasad

Department of Nuclear Engineering, University of California, Berkeley CA 94720

Abstract

In order to resolve a long-standing discrepancy of some 30 standard deviations between the two most precise previously reported values of the γ-ray energies in the ^{38}Cl decays, we have undertaken a new precision measurement of the decay energies using a variety of different sources for energy calibration. The deduced energies from the present work are 1642.668 ± 0.010 and 2167.395 ± 0.010 keV. These results agree very well with one of the previous reports and disagree with the other.

Keywords: ^{38}Cl decay [from Cl(n,γ)]. Measured γ-ray energies. ^{38}Ar deduced levels.

1. Introduction

Two previous high-resolution measurements of the γ-ray energies in the decay of ^{38}Cl to ^{38}Ar have been reported: 1642.714 (16) and 2167.406 (9) keV by Warburton *et al.* (1986) and 1642.32 (1) and 2167.71 (1) keV by Antony *et al*. (1988). (The uncertainties in the last digit or digits are given in parentheses.) These two sets of values are in significant disagreement with each other by some 30 standard deviations. Other reported measurements of these energies in the ^{38}Cl decay [as summarized in the most recent Nuclear Data Sheets (NDS) by Cameron and Singh (2008)] have uncertainties at least an order of magnitude larger and so cannot help in resolving these disagreements, nor do any of the independent determinations of the transition or level energies in ^{38}Ar. As a result, the NDS uses an average of these discordant values in arriving at the recommended energies, with the uncertainty of the average increased by an order of magnitude to account for the differences.

In order to resolve this discrepancy, we have undertaken a new measurement of the energies of the γ rays in the decay of ^{38}Cl. The results of those measurements are discussed in the present report, along with a determination of the deduced level energies in ^{38}Ar. We also report values for the relative intensities of the γ rays.

2. Experimental details

Sources of ^{38}Cl were prepared by neutron irradiation of samples of NH_4Cl powder (approximately 3 mg) in the pneumatic transfer facility of the Oregon State University TRIGA reactor. The activity of the samples was about 20 μCi (0.75 MBq) at the start of counting. The γ rays were observed with two different Ge spectrometers having efficiencies of the order of 30-40% (compared with NaI for the 1332-keV γ ray) and resolution (FWHM) of 2.5 keV for the 1643-keV γ ray. This resolution is slightly larger than optimal (typically 2.0 keV at 1643 keV), owing to the high counting rates used for this experiment, which produced dead times of around 30% in the counting system. However, the peak separations were large enough that the resolution did not adversely affect the experiment. The Ge detectors were coupled to computer-based digital data acquisition systems.

For energy and efficiency calibration, one of the spectrometers counted Cl samples together with a source of ^{56}Co, while the other spectrometer counted Cl samples simultaneously with sources of ^{24}Na, ^{56}Mn, ^{60}Co, ^{124}Sb, ^{152}Eu, and ^{207}Bi (the Na, Mn, and Sb sources were also produced by neutron activation). Calibration energies were taken from the recommended values of Helmer and van der Leun (2000). Two different Cl samples were counted in each spectrometer. Each sample was counted over several decay halflives and was moved closer to the detectors as necessary to maintain the high counting rates necessary for good statistics. Figure 1 shows a sample spectrum of the Cl and ^{56}Co sources, and Figure 2 shows the Cl source with the multiple calibration sources.

Two methods were used for determination of the peak energies: (1) Centroids were located by calculating a weighted "center of gravity" of the peak above a linear background. Peak to background ratios were greater than 10:1 for both the Cl and calibration lines. (2) Centroids were located by fitting the peak to a Gaussian shape with high and low exponential tails using fitting code SAMPO (Aarnio *et al.,* 1988) For both methods, a quadratic fit of centroid channel as a function of energy was done in regions that encompassed the Cl peaks (1038-3253 keV for both Cl peaks with the ^{56}Co calibration source; 1332-1770 keV for the 1643-keV peak and 1691-2754 keV for the 2167-keV peak with the multiple calibration sources). The summing and fitting methods produced results that differed on the average by less than 10 eV.

3. Results

Table 1 summarizes the results for the two samples observed with each of the two spectrometers, one (detector A) using the ^{56}Co calibration and the other (detector B) the multi-source calibration. The statistical uncertainties in the energies of the two stronger lines are in the range 0.003-0.005 keV for each individual result in Table 1; however, we think this underestimates the true uncertainty of the experiment. The normalized chi-squared of the quadratic fit to the calibration lines produces values in the range of 3 to 8. This perhaps suggests the presence of systematic uncertainty in the energy calibration that we can account for by increasing the uncertainty of each individual result by the

square root of the chi-squared value, thereby in effect forcing the chi-squared value to unity. This adjustment would increase the uncertainties in our results to 0.008-0.010 keV.

Taking the unweighted average of the 4 results in Table 1 yields the following values for the energies of the two stronger lines: 1642.668 keV (std. dev. = 0.011 keV) and 2167.395 keV (std. dev. = 0.010 keV). The standard deviations suggest that the variations among the 4 values are quite consistent with an uncertainty estimate of 0.010 keV.

The energy of the 3810-keV γ ray was determined only with the ^{56}Co calibration source. Its larger uncertainty represents not only the low statistical precision due to the small intensity of that line but also the additional uncertainty that results from extrapolating the energy calibration beyond the highest-energy ^{56}Co γ rays. The weighted average of the two results gives an energy of 3809.978 (64) keV.

The results of the present work for the energies of the ^{38}Cl γ rays are summarized in Table 2 and compared with previous results. It is clear that the present results are in very good agreement with those of Warburton *et al.* and in total disagreement with those of Antony *et al.* The small difference between the present results and Warburton's (which amounts to about 2 standard deviations for the 1642.7-keV transition) is reduced even further when we account for the changes in the accepted values of the ^{56}Co calibration energies between the time of their work (Helmer *et al.*, 1979) and the time of the present

work (Helmer and van der Leun, 2000), which would reduce the deduced energies of Warburton *et al*. by about 12 eV for 1642.7 keV and 15 eV for 2167.4 keV. The remaining difference is then just over 1 standard deviation for 1642.7 keV. The agreement is even better for the 2167.4-keV transition.

The ^{56}Co γ rays also serve as intensity standards for efficiency calibration (Baglin, 2002). Normalizing to the 2167.4-keV intensity, our deduced relative intensities of the ^{38}Cl lines are shown in Table 3. The 1642.7-keV intensity was obtained only from detector A (with simultaneous efficiency calibration from the ^{56}Co lines). Although the statistical contribution to the intensity uncertainty is small (typically about 0.3% for each data set), we adopt a more conservative estimate of 0.5% for the systematic uncertainty of our efficiency calibration, as recommended by Debertin and Helmer (1988). Our value for the relative intensity of the 1642.7-keV γ ray is the unweighted average of the results from the two samples, with an intensity of 0.5%. For the 3810.0-keV line, the small intensity gives a statistical uncertainty of order 10%, which is compounded by the efficiency extrapolation and then magnified even further by the subtraction of the intensity from true and accidental coincidence summing (which amounts to 20-30% of the total peak intensity). The final value in Table 3 is the weighted average of the four individual results.

Our intensity values are in good agreement with the results of the measurements of Miyahara *et al.* (1996), 74.77(41) and 0.62 (4) for respectively 1642.7 and 3810.0 keV, and with that of Hayashi *et al.* (2000), 74.96(11) for 1642.7 keV.

4. Discussion and conclusions

After correcting for the recoil energy (38 eV for 1642.7 keV and 66 eV for 2167.4 keV), the deduced energies of the ^{38}Ar excited states based on the present values of the γ-ray energies are 2167.461 (10) keV for the 2^+ first excited state and 3810.167 (14) keV for the 3^- third excited state. As with the transition energies, we agree with the level energies of Warburton and disagree with those of Antony.

The E3 crossover transition from the third excited state to the ground state is very weak compared with the direct E1 transition to the first excited state, but it is nevertheless observable. Based on our deduced energy for the 3^- level, we would expect the energy of the crossover transition to be 3809.962 keV (after correcting for the 205-eV recoil energy), in excellent agreement with the measured value given in Table 1.

Our deduced value for the energy of the 2^+ state disagrees with the adopted NDS value, 2167.64 (5) keV, which was determined primarily from an average of the Warburton and Antony results, the uncertainty in the average having been increased by nearly an order of magnitude in the NDS compilation to account for the discrepancy between those results. The ^{38}Cl decay studies previous to Warburton had uncertainties at least an order of magnitude larger and thus do not contribute significantly to the average, and owing to their large uncertainties they do not seem to favor either of the more precise values.

While the 2^+ state is populated in other decay and reaction studies (as summarized by Cameron and Singh, 2008), none has a precision even close to that of the ^{38}Cl studies and thus they do not help to resolve the energy discrepancy.

The present value for the 3^- energy agrees with the less precise NDS value, 3810.16 (6) keV, determined again from an average of the Warburton and Antony results with the uncertainty increased by nearly an order of magnitude. This agreement is in some sense accidental, because the Warburton and Antony results for the energies of the $3^- \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions are discordant in opposite directions such that the discrepancies nearly cancel when they are added; thus they give similar values for the energy of the 3^- level (after correcting Antony's value of the level energy for the nuclear recoil).

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Table 1. Measured energies (in keV) of ^{38}Cl γ rays.

Detector	Sample	γ_1	γ_2	γ_3
A	1	1642.667	2167.391	3809.865 (166)
	2	1642.658	2167.396	3809.998 (70)
B	1	1642.683	2167.407	
	2	1642.662	2167.382	

Table 2. Energies (in keV) of ^{38}Cl γ rays.

	Present work	Warburton *et al.*[a]	Antony *et al.*	NDS
$3^- \rightarrow 2^+$	1642.668 (10)	1642.714 (16)	1642.32 (1)	1642.43 (8)
$2^+ \rightarrow 0^+$	2167.395 (10)	2167.406 (9)	2167.71 (1)	2167.54 (7)
$3^- \rightarrow 0^+$	3809.978 (64)		3810.03 (7)	3810.03 (7)

[a]Changes in the accepted energies of the calibration lines since the publication of this work would reduce the reported energies of the 2 γ rays by respectively 12 and 15 eV

Table 3. Intensities of γ rays in the decay of ^{38}Cl.

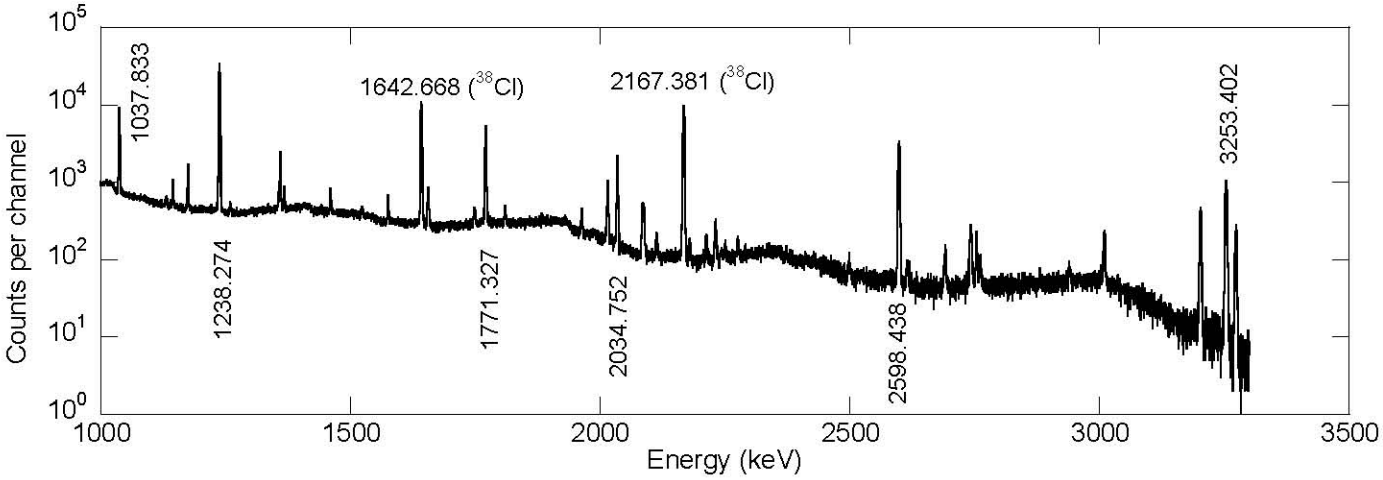
Detector	Sample	1642.7	2167.4	3810.0[a]
A	1	75.2	100.0	0.076 (23)
	2	75.8	100.0	0.084 (21)
B	1		100.0	0.061 (22)
	2		100.0	0.068 (15)
Average		75.5 (4)	100.0 (5)	0.071 (10)

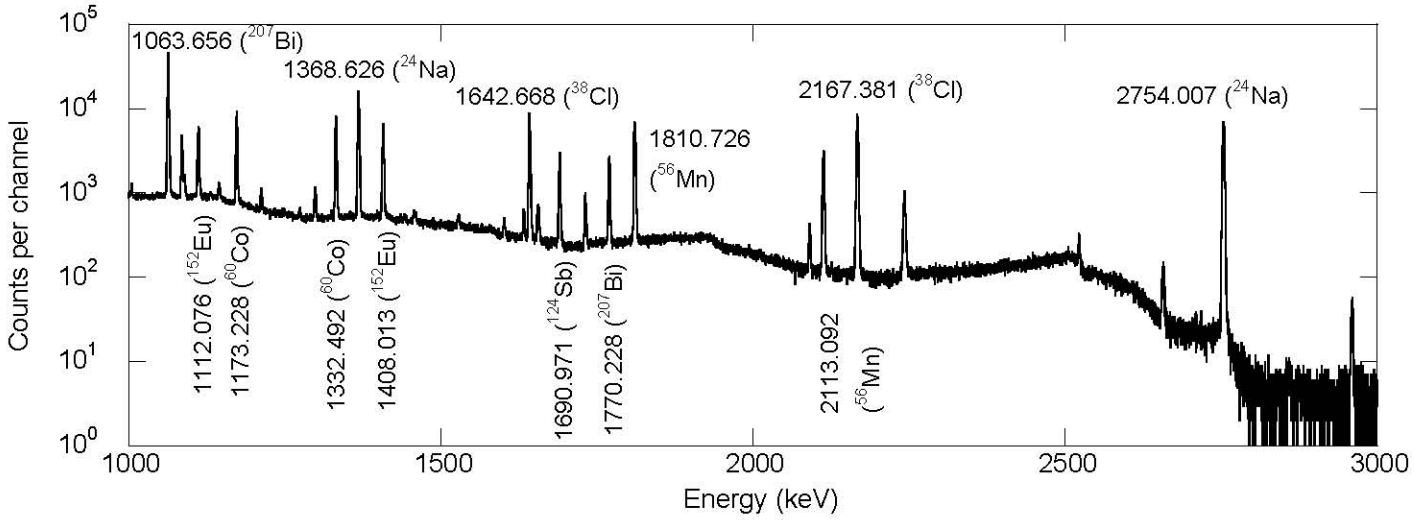
[a]Corrected for true and accidental coincidence summing.

FIGURE CAPTIONS

Fig. 1. Partial γ-ray spectrum of ^{38}Cl source with ^{56}Co calibration source.

Fig. 2. Partial γ-ray spectrum of ^{38}Cl source with multiple calibration sources.


Counts per channel
Energy (keV)
1037.833
1238.274
1642.668 (^{38}Cl)
1771.327
2034.752
2167.381 (^{38}Cl)
2598.438
3253.402


Counts per channel
Energy (keV)
1063.656 (207Bi)
1368.626 (24Na)
1642.668 (38Cl)
1810.726 (56Mn)
2167.381 (38Cl)
2754.007 (24Na)
1112.076 (152Eu)
1173.228 (60Co)
1332.492 (60Co)
1408.013 (152Eu)
1690.971 (124Sb)
1770.228 (207Bi)
2113.092 (56Mn)